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PERFORMANCE EVALUATION OF SHORT-RANGE PF-GIPOF LINKS: ON DISCRETE MULTI-TONE TRANSMISSION AND WDM ENHANCEMENT

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Abstract: This paper analyzes the achievable capacity in PF GIPOF short-range links (<200m) by combining both the Wavelength Division Multiplexing (WDM) approach and the discrete multitone (DMT) modulation scheme operating in a single channel. The fact that the PF GIPOF may build up the base for future WDM systems is demonstrated, overcoming the power penalty in the system due to the addition of future GIPOF-based WDM devices.

Key words: PF Graded-Index Polymer Optical Fiber (GIPOF), Discrete Multitone (DMT) Modulation, Wavelength Division Multiplexing (WDM), transmission capacity.

1. Introduction

Growing research interests are focused on the high-speed telecommunications and data communications networks with increasing demand for accessing even from the home, due to the huge successes during the last decade of new multimedia services (high-definition (HD), three-dimensional visual information (3D) or remote “face-to-face communication”) which forecast requirements for data transmission speed more than 40Gbps by 2020, which can be achievable only with optical network [1]. Regarding this data transmission capability, Perfluorinated Graded-Index Polymer Optical Fiber (PF GIPOF) has emerged as a useful medium for access network and data center connections but its potential capacity for communication needs a greater exploitation to meet user requirements for higher-data rates.

To extend the capabilities through optical fibers, different efficient and advanced modulation formats and/or adaptive electrical equalization schemes can alternatively be applied [2, 3]. Considering the industry’s extensive experience and the large economies of scale, orthogonal frequency division multiplexing (OFDM) and discrete multitone modulation (DMT) are seen as promising technologies for low-cost, reliable, and robust Gigabit transmission through hundreds of meters of Polymer Optical Fibers (POF). Particularly, DMT modulation has been demonstrated to achieve near-optimum performance and to enable highly spectral efficient transmission at high bit-rates over silica multimode fibers (MMFs) and POFs [4].

On the other hand, Wavelength Division Multiplexing (WDM) techniques over POFs have also been considered [5] to further increase such data transmission capacity. Apart from the physical transmission characteristics of POF, it is equally important to consider the optical components introduced to deploy advanced WDM-based architectures. A typical WDM optical communication link requires, at the very least, both a multiplexer and a demultiplexer which provide additional insertion loss into the system. This results in a decrease of the available optical power budget of the system leading to a bit-rate penalty. Most of the POF-based mux/demux prototypes reported in literature have been developed on the basis of interference filters and diffraction gratings. However, it has been previously stated that the use of gratings for WDM-POF applications probably leads to the best results in terms of insertion loss [6] in which typical insertion losses of ~5dB are usually expected. These latter attempts have been mainly conducted on Step-Index PMMA-POFs but with some exceptions. In the work reported in [7] a 2.5Gbps per channel over a 84m-long PMMA-GIPOF was achieved by using a grating as a demultiplexing filter. WDM devices for PF-GIPOFs have also attracted the interest of the POF community [8, 9].

In this work, the capacity transmission using DMT modulation with optimum rate-adaptive water-filling algorithm over PF-GIPOFs is compared for both a single channel operation and a 4- λ WDM system, respectively. An overview of DMT capabilities over PF-GIPOF in single channel operation is analyzed by means of its measured frequency response. Finally, the capacity of the WDM extension is also evaluated, assuming that DMT is the best solution for both scenarios.

2. PF GIPOF single channel capacity

In this section, the capacity of a PF-GIPOF in single channel operation and applying DMT modulation is analyzed by means of its -3dB baseband bandwidth values (f_{3dB}) for different lengths. This type of fiber has been demonstrated to enable robust 2GbE (GbE, Gigabit Ethernet) and 10GbE baseband transmission over short reach distances ranging from 25m up to 100m for different link scenarios [10]. These capacity values are considered as an underneath estimation of the transmission limit of PF GIPOFs as complex modulation formats, restricted mode launching schemes, equalization techniques or simultaneous data transmission over high-order latent PF-GIPOF passbands can be applied to enhance its aggregated capacity. Previous works [11, 12] have reported the measured and theoretical frequency responses for different lengths of a 50 μ m core diameter PF-GIPOF link under Overfilled launching (OFL) condition and employing a Fabry-Perot (FP) laser source operating at 1300nm, thus assuring equilibrium mode distribution. From those measurements PF-GIPOF f_{3dB} values for different fiber lengths can be easily identified. Results are listed in Table 1.

Table 1.- Calculated theoretical capacity over 50 μ m core diameter PF-GIPOF, at 1300nm.

Length (m)	Measured electrical -3dB bandwidth (GHz)	Capacity (Gbps)
25m	17.6	641.6
50m	8.7	320.7
75m	6.2	218.1
100m	2.7	98.1
125m	1.4	51.1
150m	1.3	43.3

- a) Average transmitted optical power=0dBm;
- b) Fiber attenuation@1300nm= 55dB/km;
- c) Clipping factor=3;
- d) Noise equivalent power: NEP= $12 \cdot 10^{-12}$ W/ $\sqrt{\text{Hz}}$

It is a matter of fact that the resulting theoretical Shannon capacity of an optical fiber channel can be calculated if its f_{3dB} is known [2, 13], modeled as a Gaussian low-pass filter. It is also important to consider the operation temperature as some transfer function fluctuations are expected depending on the temperature operation range [14]. The PF-GIPOFs used are commercially available from Chromis Fiber with an attenuation of 55dB/km at 1300nm. For the frequency response measurements, the FP laser diode used as transmitter was externally AM modulated with a RF sinusoidal signal (up to 20GHz of modulation bandwidth), by means of an electro-optic (E/O) Mach-Zehnder modulator (16GHz bandwidth), and an InGaAs-photodetector (22GHz bandwidth) was used as receiver. Bandwidth limitation from both transmitter and receiver can therefore be neglected for links >50m. The resulting channel capacity, which is calculated based on the measured f_{3dB} fiber link and the transmission characteristics shown at the right column, is shown in Table 1 for each case. For some applications, e.g. home network Ethernet transceivers, eye safety operation is required and a limited averaged transmitted optical power of 0dBm has been considered. A capacity of hundreds of Gbps can be achieved up to 75m-long PF-GIPOF link from the results shown in Table 1. Nevertheless, modeling the PF-GIPOF as a Gaussian low-pass filter reveals as a pessimistic approximation of the PF-GIPOF channel response due to the presence of high-order passbands in its frequency response [11], and actual capacity values of PF-GIPOF can be larger than those reported within Table 1, even greater if Restricted Mode Launching (RML) schemes are applied to the injection of light into the fiber.

On the other hand, DMT allows the possibility to allocate the number of bits and energy per subcarrier according to its corresponding signal-to-noise ratio (SNR), typically known as bit-loading. As Chow's algorithm has been shown to achieve near-optimum performance [15] the latter will be used to compute rate-adaptive bit-loading for the DMT over PF GIPOF consideration. Initially, all sub-channels were loaded with 4 information bits each. Table 2 shows the results based on PF-GIPOF frequency response measurements. Compared to the results given in Table 1, it can be seen that for the shortest length (25m), the numerically computed capacity value is lower than the theoretical counterpart. This results from bandwidth limitation of the external modulator bandwidth, considered in the computation. From lengths > 50m, the computed capacity is larger because the PF-GIPOF frequency response dominates over other bandwidth limitation factors. Due to the bandwidth limitation of the PF-GIPOF link itself, the signal-to-noise-ratio decreases for higher frequencies. The best carriers at low frequencies enable a 256-QAM to 512-QAM modulation, see Fig. 1.

Table 2.- Theoretical DMT capacity over 50 μ m core diameter PF-GIPOF, at 1300nm.

Length (m)	Numerical DMT over PF GIPOF Capacity (Gbps)
25m	616.6
50m	329.6
75m	236.9
100m	114.3
150m	65.7

Note: targeted BER= 10^{-3}

3. WDM extension in PF GIPOF links

For flexible high capacity GIPOF optical networks, applying WDM seems to be necessary. In this section a general picture of the PF-GIPOF transmission capacity using DMT modulation and operating in both a single channel link and a 4- λ WDM extension is presented. Apart from the physical transmission characteristics of the PF-GIPOF, it is equally important to consider the optical components that are available to implement advanced WDM-based optical architectures. This is the case of WDM multiplexers (MUX)/demultiplexers (DEMUX) which are mainly manufactured only in SMF and are not (yet) available for MMF/POF/GIPOF, being the latter mostly limited to prototype versions based on gratings. Nevertheless, PF GIPOFs can take advantage of the relatively low attenuation at 850nm, suitable for directly modulated vertical-cavity surface emitting lasers (VCSELs) as well as at 1.3 μ m, where off-the-shelf Fabry-Perot (FP) and Distributed Feedback (DFB) laser diodes operate.

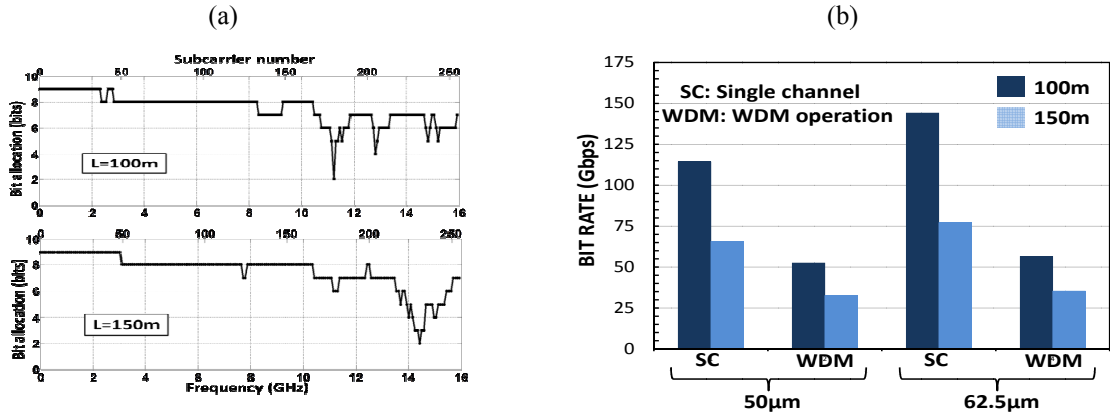


Fig. 2. (a) Theoretical bit loading when 4- λ WDM over PF-GIPOF is considered in the link. (b) Comparison of single channel and one- λ WDM operation over 100m and 150m PF GIPOF (at 1300 nm).

As a last step, we recalculate the PF-GIPOF transmission capacity from: a) the new bit loading resulting from the DMT modulation scheme and, b) the restriction on power margin resulting from the new losses considered in the system due to the addition of the MUX/DEMUX devices in the optical link. We assume an insertion loss for a future PF-GIPOF 4- λ multiplexer/demultiplexer device to be around 2dB [8, 9], lower to the expected losses of PMMA-SIPOF based MUX/DEMUX [16]. Consequently, the power budget of the WDM system consisting of a POF-based multiplexer and demultiplexer device is reduced in 5dB per channel, if an optical crosstalk of 1dB is considered. This reduction of the OSNR (optical SNR) performance of the system, results in a dramatic decrease of the possible bit rate per channel. On the other hand, some authors have evaluated power penalties close to 2.4dB when combining a 62.5 μ m core diameter PF-GIPOF and WDM devices based on 50 μ m core diameter MMF [17]. Fig. 2a shows the theoretical bit loading including the aforementioned restriction in power budget. The corresponding aggregated capacity is summarized in Fig. 2b. Capacity values for a 62.5 μ m core diameter PF-GIPOF following the same procedure and under the same constraints are also shown (from its frequency response measurements). Greater capacities can be achieved as increasing the core diameter due to the presence of strong mode coupling effects and less modal noise effect.

The achievable capacity of a single- λ WDM system does not reach the best single channel results, but being only around two times lower compared to that of obtained in single channel operation, if we focus on the results displayed for 50 μ m core PF-GIPOFs. This is due to the fact of its larger bandwidth available compared to the step-

index POF evaluated in [18]. Therefore, assuming a 4- λ WDM system using the full available optical power and with similar bit rate transmission performances in each channel, as those shown in Fig. 2b, the total achievable capacity would overcome the OSNR and bit-rate limitation due to the optical losses introduced in the power budget of the system. Improvements on mux/demux manufacturing would make PF-GIPOF WDM systems a future-proof and feasible solution for in-home/building networks to attend users' high-speed demands.

4. Conclusions

Applying WDM can further enhance the transmission capacity via PF-GIPOF. The achievable transmission rate of DMT over different PF GIPOF lengths is studied by using rate-adaptive bit-loading algorithm. Due to the PF GIPOF lower attenuation and higher transmission capacity compared to other POF solutions, the achievable aggregated capacity of the PF-GIPOF WDM approach overcomes the power budget penalty introduced by the addition of mux/demux devices. We believe the results reported in this work may encourage the development of PF-GIPOF WDM network, and the availability of low insertion loss PF-GIPOF-based WDM devices will open up the path for future in-home systems at very high bit rates.

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